PB88-214788

Analysis of Crop Loss for Alternative Ozone Exposure Indices

(U.S.) Corvallis Environmental Research Lab., OR

May 88

U.S. Department of Commerce
National Technical Information Service
NTIS

PB88-214788

EPA/600/D-88/118
May 1988

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U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/D-88/118	2.
3. RECIPIENT'S ACCESSION NO. PB88 214788/AS	
4. TITLE AND SUBTITLE Analysis of Crop Loss for Alternative Ozone Exposure Indices	5. REPORT DATE May 1988
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) David T. Tingey, William E. Hogsett and E. Henry Lee	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS US EPA and Northrop Services, Inc. Corvallis	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED Symposium Paper
	14. SPONSORING AGENCY CODE EPA/600/2

15. SUPPLEMENTARY NOTES -

16. ABSTRACT

A goal of air pollutant research is to determine the relationship between pollutant exposure and plant response. The quantifying function for this process is frequently termed "dose-response". However, in this discussion of exposure dynamics it will be termed "exposure-response", a more generic concept. An understanding of exposure response requires three types of information: 1) a measure of plant response; 2) an appropriate index to describe the pollutant exposure; and 3) a mathematical function that relates plant response to pollutant exposure. Defining the appropriate exposure index that "best" relates plant response to exposure necessitates a consideration of the underlying biological basis for the response and a method for characterizing the temporal variations in pollutant occurrence.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 1
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

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INTRODUCTION

A goal of air pollutant research is to determine the relationship between pollutant exposure and plant response. The quantifying function for this process is frequently termed "dose-response". However, in this discussion of exposure dynamics it will be termed "exposure-response", a more generic concept. An understanding of exposure response requires three types of information: 1) a measure of plant response; 2) an appropriate index to describe the pollutant exposure; and 3) a mathematical function that relates plant response to pollutant exposure. Defining the appropriate exposure index that "best" relates plant response to exposure necessitates a consideration of the underlying biological basis for the response and a method for characterizing the temporal variations in pollutant occurrence.

Plants react differentially to temporal variations in pollutant concentrations;[1,2,3,4] consequently, it is necessary to select exposure indices that specifically account for the temporal variation in exposure. If plant response were not modified by the episodic nature (temporal variation) of the exposures, then it would be sufficient to characterize the exposure with an index such as a mean that does not reflect the concentration variation over time.

In evaluating exposure indices that characterize plant response, the ultimate goal is to develop exposure indices that incorporate all contributing features and account for all (or most) of the variation in the exposure response. A second, goal is the development of exposure indices useful in the standard setting process. An index for a standard should be easy to develop and applicable to a wide range of species and environmental/exposure conditions. This objective may represent a compromise in the features included in the formulation of the "best" exposure index.

The magnitude of plant response to O_3 is altered by several components including 1) climatic and edaphic factors; 2) biological factors such as phenological stage of development and genetic variability; and 3) the temporal variation in O_3 exposure. Because these components and their influence on plant response have been recently reviewed,[3,4] this presentation will focus on the evaluation and development of exposure indices that include the temporal components of the exposure.

EVALUATION OF EXPOSURE INDICES

There is no consensus about the most appropriate exposure index (metric) for depicting plant response to O_3 exposure.[4,5] Several indices have been used, but their adequacy for characterizing long-term exposures (over a season) is doubtful, since they do not account for exposure dynamics (i.e., temporal variation). Additionally, the indices do not account for other known influences, such as effects of exposures at specific and perhaps

critical periods in plant development. Most indices, such as a seasonal mean, do not cumulate the impact of the exposure over the growing period.

An appropriate exposure index should ultimately be derived from a consideration of the underlying biological basis for the response and a procedure for quantifying the temporal variations in O_3 occurrence. An evaluation of various exposure indices is essentially a comparison of the influence of different scalings of the exposure variable on the exposure response function (Fig. 1). The comparison is based on a single set of biological responses (e.g., plant yield) but they are related to different mathematical characterizations of O_3 exposure (scales) such as a mean or a cumulation of hourly concentrations. The different indices or scalings do not change the magnitude of the measured plant response, but they do govern how these responses are positioned along the exposure axis (Fig. 1).

A pair of examples illustrates the effect of using different indices for characterizing the temporal variations in O_3 exposure (Fig. 2). In the first example (Fig. 2A, B, alfalfa plants were exposed to episodic O_3 exposures[2] and harvested (when the plants reached one-tenth bloom) three times during the season. A comparison was made between two exposure indices: (1) the 7-h (0900 to 1559) seasonal mean concentration;[6] and (2) the generalized phenologically weighted cumulative impact (GPWCI) that cumulated the exposure and emphasized the peak concentrations.[7] The fit of the same exposure-response function to the identical response data was clearly better when the GPWCI (Fig. 2B) was used to array the observed plant responses along the exposure axis than when the 7-h seasonal mean was used (Fig. 2A). With the GPWCI, the trend for reduced plant growth with increasing exposure is plainly seen; however, this pattern is not evident when the mean is used. A second example (Fig. 2C, D) is provided by a comparison of the maximum yield loss observed in a range of crop species. The evaluation of exposure indices compared the 7-h seasonal mean and the total exposure (sum of concentrations throughout the study). In this example, as in the previous one (Fig. 2A, B), there is a clear trend showing an increase in maximum yield loss with increasing exposure (Fig. 2D); however, when the 7-h seasonal mean was used this trend was not evident (Fig. 2C). The principal difference between the two indices was the inclusion of exposure duration (number of days) in the total exposure index. Several of the studies had essentially the same 7-h seasonal mean, but the study durations differed by approximately twofold which caused the lack of a clear trend in the data. In both examples, the mean was not an appropriate index (scaling factor) for describing the response of plants to long-term (e.g., growing season) exposures to episodically occurring concentrations of O_3.

The mathematical mean of the hourly O_3 concentrations, over various time periods, is frequently used to characterize pollutant exposures. The 7-h (M7) and 12-h (M12) seasonal means

have gained credence for relating plant yield to O_3 exposure because of their use in the National Crop Loss Assessment (NCLAN) program.[6,8,9] The specific 7-h period (0900-1559) selected was thought to correspond to the period of greatest plant sensitivity and the highest O_3 levels.[6] The seasonal mean concentration is a summation of all hourly concentrations (for the selected time period) divided by the number of observations. Cure et al.[8] reported that seasonal mean characterizations of O_3 exposure were not sensitive variations in O_3 patterns. An infinite number of hourly distributions (from those containing many peaks to those containing none) can yield the same 7-h seasonal mean. If a mean is selected as an exposure index for characterizing exposures, there are certain assumptions that are implied and must be considered in a study's interpretation:

- A mean tends to minimize the contributions of peak concentrations to the response, implying that peak events do not need to be given special consideration.
- All concentrations within the selected averaging time are equally effective in eliciting a response.
- Reduced crop yield results from the accumulation of daily O_3 impacts over the growing season.
- Exposure duration is not specifically included: i.e., the mean can not distinguish between exposures to the same concentration but of different durations (i.e., 10 or 100 days).
- The distribution of hourly O_3 concentrations (over the averaging time) is unimodal and not highly skewed. However, ambient O_3 concentration distributions are frequently skewed toward the higher concentrations.

Ideally, the selection of the most appropriate exposure index would be derived from scientific principles and be validated by experimental studies specifically designed for that purpose. However, this approach would delay resolving the selection of exposure indices for years until the necessary experiments were designed and conducted. An alternative approach is to conduct a retrospective analysis of existing plant-response data. This approach permits the reanalysis of existing data for evaluating or developing a range of exposure indices and deriving principles of exposure response. Nevertheless, the indices developed by this method will ultimately need to be validated experimentally. A major limitation with retrospective analysis is that the specific studies were not designed for developing exposure indices or testing exposure hypotheses; consequently the usability of the data is limited.

A retrospective analysis to evaluate existing and proposed exposure indices was conducted[7] using crop yield data obtained from the U.S. Environmental Protection Agency's NCLAN Program.[9]

Plant production and hourly O_3 monitoring data were obtained from the NCLAN Data Library in Raleigh, North Carolina. Data from field experiments on soybean, wheat, corn, sorghum, and cotton were used in the analyses. Crops were grown according to standard agricultural practices and exposed to a range of O_3 concentrations (ambient levels and above) in open-top chambers.[9]

Exposure indices were calculated from crop yield data for the five species (with multiple years and cultivars for a total of 17 individual cases). The details of the data sources and analytical procedures used in the retrospective analysis are described by Lee et al.[7] The authors evaluated six different types of exposure indices for the 17 individual cases; the various types of indices had disparate characteristics. The different types of exposure indices used in the analyses are compared in Table I and the abbreviations used in Table are described:

1. One Event: includes the maximum 7-h (P7) and maximum 1-h (P1) daily averages[6] and the 90th (PER90), 95th (PER95), and 99th (PER99) percentiles of hourly distribution.

2. Mean: includes the seasonal means[6] of 7-h daily means (M7), 1-h daily means (M1) and the effective mean[10] (EFFMEAN).

3. Cumulative: represents the seasonal sum of all hourly concentrations (over the 7-h period, 0900-1559), i.e., total exposure (TOTDOSE).

4. Concentration Weighting: Two separate types of weighting indices were used;

   - Sum Concentration (Sum Conc) indices cumulated the exposure and used either discontinuous or continuous weighting of concentration.[4] The discontinuous indices included seasonal sum of hourly concentrations at or above 0.06 ppm (SUM06), 0.07 ppm (SUM07), 0.08 ppm (SUM08), or 0.10 ppm (SUM10); seasonal censored sum of hourly concentrations at or above a threshold, i.e., cumulative sum of the area over threshold of 0.08 ppm (AOT08) or 0.10 ppm (AOT10). The continuous indices included total impact[11] (TIMPACT); ALLOMETRIC in which the hourly concentration was raised to a power and summed; and SIGMOID in which the hourly concentration was multiplied by a sigmoid weighting function (inflection = 0.062 ppm) and summed.[7]

   - Number of Episodes (Num Episodes) indices counted the episodes over the exposure period. This type of index included total hours with concentrations at or above thresholds of 0.08 ppm (HRS08) or 0.10 ppm (HRS10); the number of episodes above a threshold of 0.08 ppm (NUMEP08) or 0.10 ppm (NUMEP10); and average episode length using thresholds of 0.08 ppm (AVGEP08) or 0.10 ppm (AVGEP10).

5. Multicomponent: these indices incorporate several

characteristics of exposure.[4] Lee et al.[7] evaluated a number of multicomponent indices (>500) that included different weightings for concentration and phenological stages of development. This evaluation uses their[7] "best" multicomponent index (GPWCI) which has the following features: 1) a sigmoid concentration weighting function (inflection point = 0.062 ppm), 2) exposures occurring 20 to 40 days before harvest were given maximum weight, and 3) the weighted hourly concentrations were cumulated for the exposure period.

6. Respite Time: the average number of days between episodes (an episode was defined as an event with hourly O_3 concentrations above a threshold value) using threshold values of 0.08 ppm (DAYBET08) or 0.10 ppm (DAYBET10).

The exposure indices were computed from actual hourly O_3 monitoring data and regressed against individual chamber harvest yields using the Box-Tidwell model.[7] The "best" exposure index for each set of response data (case) was the one displaying the minimum residual sum of squares (RSS). For an individual set of exposure-response data, the relative performance of any index was measured as the ratio of its RSS to the exosure index with the minimum RSS and ranked in ascending order, i.e., the "best" index for a give case would have a relative RSS of 1. For overall comparison among data sets, the exposure indices were evaluated according to three criteria: (1) the average score calculated as the mean relative RSS's averaged across the 17 cases; (2) the range of relative RSS's; and (3) percent variation, (i.e., [range/mean score] x 100). The nonparametric Wilcoxin signed ranks test was used to perform pairwise comparisons of relative RSS's among indices across cases. [12]

No single exposure index performed "best" (based on minimum RSS) for all plant species/cultivars, but there was positive agreement among the top-ranked indices for the 17 cases.[7] A comparison of the 27 indices used found that 20 had average scores of 1.20 or larger (Table 1). The paired sample Wilcoxin signed ranks test showed no significant differences (at the 0.05 level) between the top-ranked index (GPWCI) and other indices which also gave greater weight to elevated concentrations and cumulated the exposures (SUM07, SUM06, SIGMOID, SUM08, AOT08, ALLOMETRIC, AOT10, SUM10). The weighted cumulative indices SUM07, SUM06, and SIGMOID had similar average scores (1.14, 1.15, and 1.17 respectively) and displayed similar percent variations to the top-ranked GPWCI index across all species/cultivars. Although the SUM08, AOT08, and PER99 indices were not significantly different than the top-performing index, they displayed greater percent variation than the top-performing GPWCI index. In particular, the noncumulative index, PER99, had relative fits ranging from 1.00 to 2.06 across the cases, which represents a threefold increase over the top-performing GPWCI's range of relative RSS's. Three indices, ALLOMETRIC, SUM10, and AOT10, had average scores greater than 1.20, but were not significantly

different than the top-ranked GPWCI index due to an extremely poor fit in a single case (the 1981 cotton study with drought-stressed plants). Based on our criteria, SUM07, SUM06, and SIGMOID were nearly equal in performance to the top-ranked GPWCI index. Based on average score and variation, the M7 performed better than PER99 (non-cumulative indices), but its performance was significantly inferior to the four top-ranked indices (GPWCI, SUM07, SUM06, and SIGMOID). For these analyses, the exposure indices that emphasize peak concentrations and cumulate concentrations over time performed better than those that used only average concentrations.

Similar conclusions were reached by Lefohn et al.[13] and Lee et al.[14] who used NCLAN data and cumulative indices with sigmoid[13] and allometric[14] concentration weighting functions. The recent work of Lee et al.[7] found that the sigmoid-weighting functions were preferred to allometric ones. The GPWCI indices with sigmoid weights (which emphasized concentrations >0.06 ppm) performed better than did discontinuously weighted cumulative exposure indices that ignore hourly concentrations below thresholds of 0.08 ppm. However, the discontinuously weighted cumulative indices (SUM07 and SUM06) that used threshold concentrations (0.06 or 0.07 ppm) to emphasize concentration and accumulated exposure performed similarly to the top-ranked GPWCI index.

CONCLUSION

Our analyses support the conclusions from previous studies that demonstrated the importance of peak concentrations in determining plant response. Although no single index was deemed "best" (in all cases) for relating O_3 exposure to plant response, the top-performing exposure indices were those that (1) cumulate the hourly O_3 concentrations over time, (2) emphasize concentrations of 0.06 ppm and higher either by continuous sigmoid weights or by discrete (0 or 1) weights of the threshold indices, and the "best" index gave greater weight to exposures occurring 20 to 40 days before harvest. When assessing the impact of O_3 on plant growth, these findings illustrate the importance of exposure duration, the importance of repeated peaks, and the time of increased plant sensitivity.

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TABLE I. Comparison of various exposure indices.

Exposure Index	Mean Score	Minimum Score	Maximum Score	Range	% Variation	Index Type
GPWCI	1.12	1.02	1.36	0.34	30	Multicomponent
SUM07	1.14	1.01	1.32	0.31	27	Sum Conc
SUM06	1.15	1.04	1.38	0.34	30	Sum Conc
SIGMOID	1.17	1.04	1.35	0.31	26	Sum Conc
SUM08	1.17	1.05	1.54	0.49	42	Sum Conc
AOT08	1.18	1.01	1.80	0.79	67	Sum Conc
PER99	1.19	1.00	2.06	1.06	89	One Event
TIMPACT	1.20	1.01	1.70	0.69	58	Sum Conc
EFFMEAN	1.20	1.02	1.65	0.63	52	Mean
M7	1.20	1.02	1.63	0.61	51	Mean
TOTDOSE	1.21	1.02	1.63	0.61	50	Cumulative
ALLOMETRIC	1.22	1.01	1.74	0.73	60	Sum Conc
PER90	1.22	1.01	1.86	0.85	70	One Event
PER95	1.23	1.00	1.99	0.99	80	One Event
AOT10	1.24	1.02	2.84	1.82	147	Sum Conc
M1	1.26	1.02	2.11	1.09	87	Mean
SUM10	1.27	1.00	2.96	1.96	154	Sum Conc
P7	1.31	1.00	2.32	1.32	101	One Event
P1	1.40	1.07	2.34	1.27	91	One Event
NUMEP08	1.40	1.00	2.04	1.04	74	Num Episode
HRS10	1.43	1.00	4.67	3.67	257	Num Episode
AVGEP08	1.46	1.01	4.93	3.92	268	Num Episode
HRS08	1.49	1.05	5.07	4.02	270	Num Episode
AVGEP10	1.74	1.00	4.08	3.08	177	Num Episode
NUMEP10	1.78	1.03	5.46	4.43	249	Num Episode
DAYBET10	4.49	1.37	15.20	13.83	308	Respite Time
DAYBET08	5.35	1.49	17.00	15.51	290	Respite Time

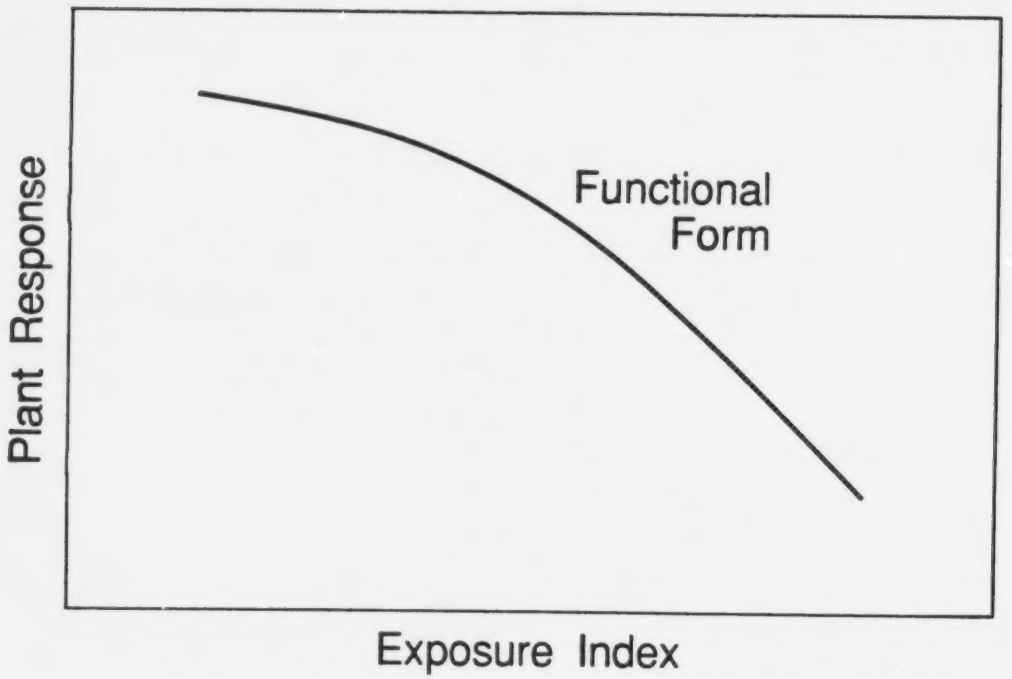

Figure 1. An example of a hypothetical exposure-response function illustrating the three key elements in understanding exposure dynamics. The exposure index connotates a description of O_3 exposure and is used as a scaling factor.

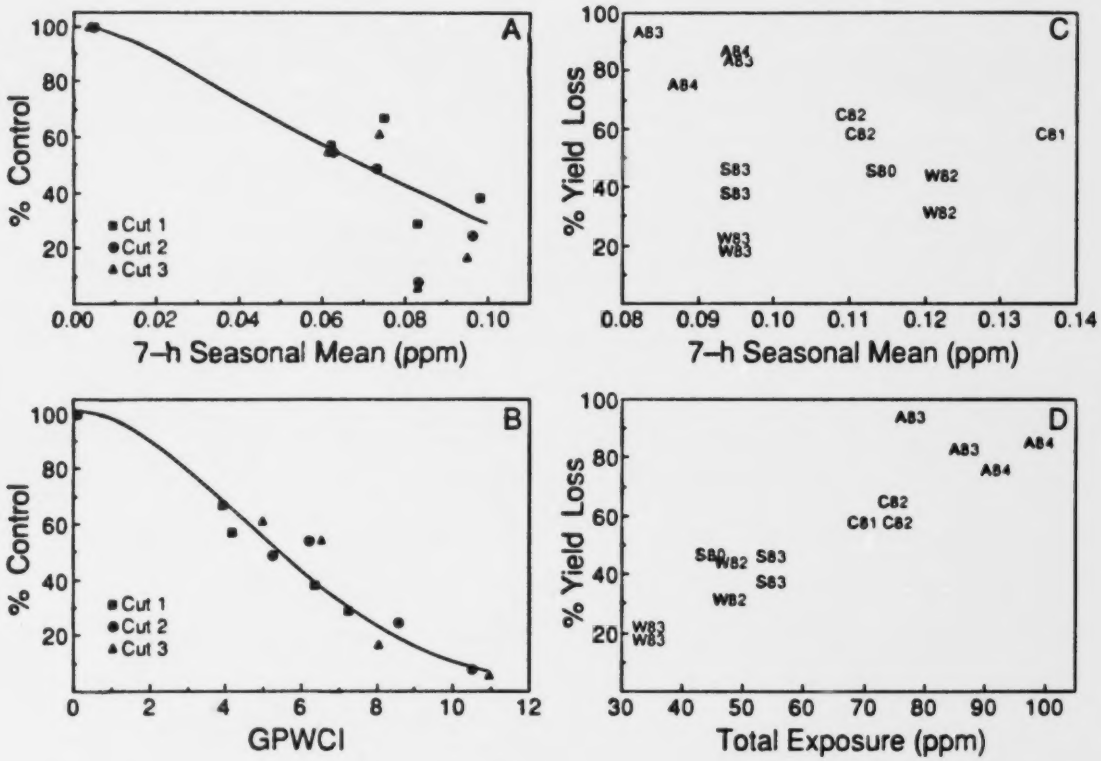

Figure 2. Two comparisons of different exposure indices using the same biological response data. The data in Figure 2A and B were derived from Hogsett et al.[2] and the data in Figure 2C and D are from Lee et al.[14] The R^2 for the data in Figure 2A and B are 0.64 and 0.90, respectively. In Figure 2C and D, the symbols indicate the year of the study and the species used; A = alfalfa, C = cotton, S = soybean, W = wheat. The R^2 for the data in Figure 2C and D are 0.27 and 0.92, respectively.